



300 mm XRD METROLOGY – Ensuring Thin Film Reliability in Microelectronics

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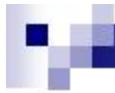
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914 945-1012



SUMMARY

- R_s measurements will not work at << 10 nm film thickness
- X-ray diffraction metrology tool - **metal thickness, crystallographic phase and texture** in a time frame suitable for 300 mm online applications developed
- Speed, precision and mapping capabilities
 - process qualification
 - process development
 - process stability (metrology)



Outline

- Thin Film Reliability – EM, SV,
 - Why measure film texture?
- Techniques
 - Four-Circle Goniometer, Area Detector, EBSP, TEM,
 - HyperNeX – Metrology Tool Development
- Results
- Conclusions

Time Dependent Failure Mechanisms

Gradients

Electric Field, E
Temperature, T
Concentration (μ), c

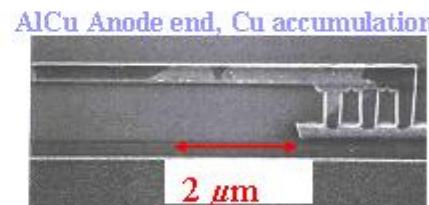


Fluxes

Current
Heat Flow
Diffusion

Diffusion - Kinetic Model

$$J_{\text{atoms}} = -J_{\text{vacancies}}$$



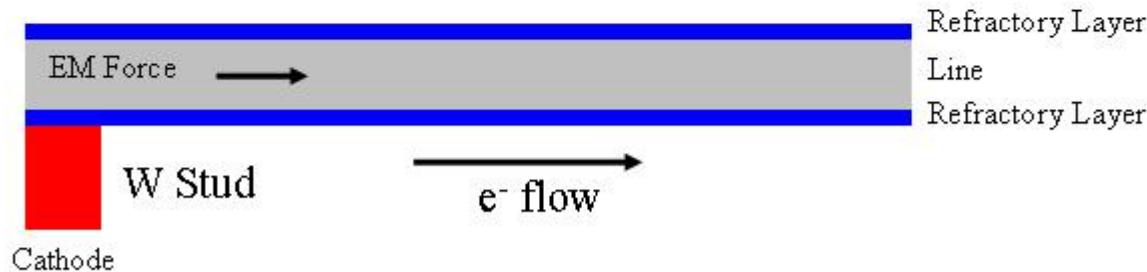
$$J_{\text{atoms}} = L_1 \frac{dc}{dx} + L_2 E + L_3 \frac{dT}{dx} + L_4 \frac{d\sigma}{dx}$$

**“Microstructure” sets the boundary conditions
and sets the sinks and sources of vacancies**

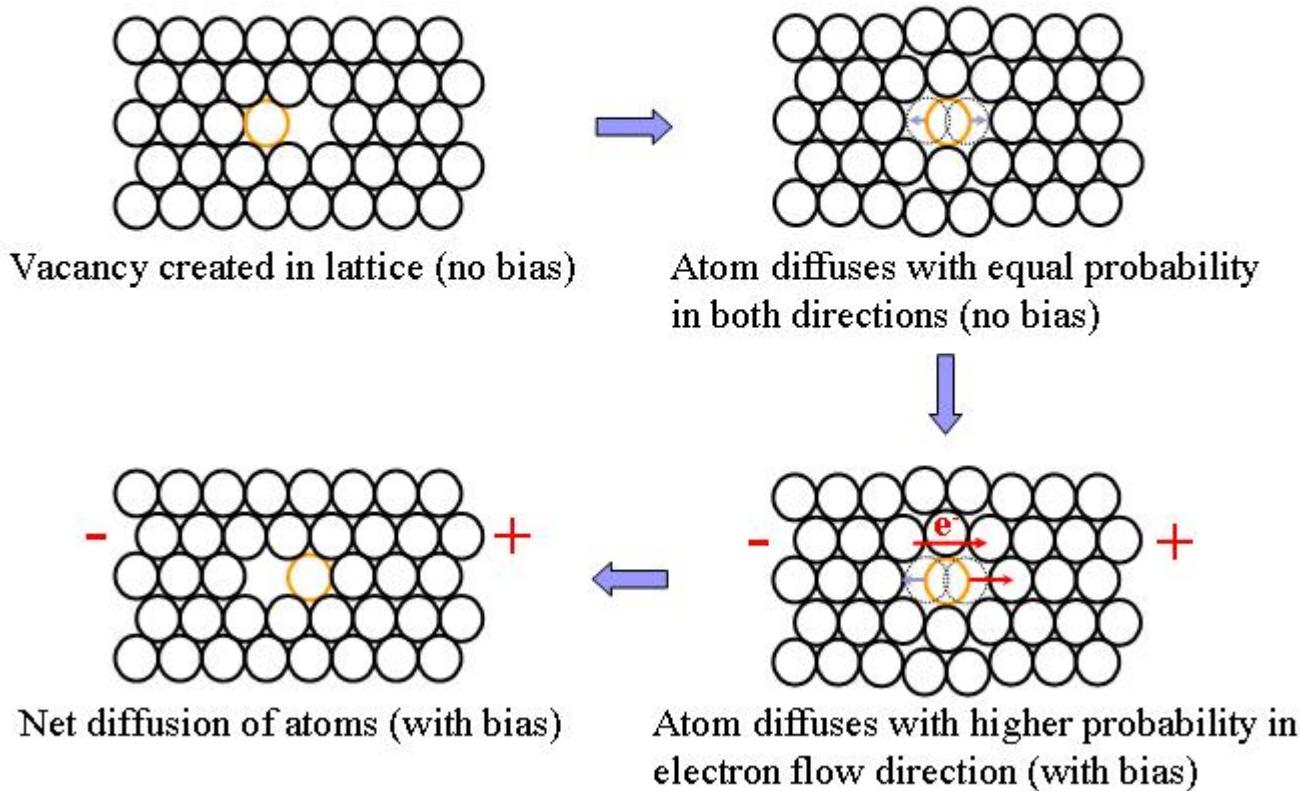
Physical Mechanism –

During electromigration (EM), the electron wind applies a force that results in an atomic flux, J

$$J = n v_e = n \left(\frac{D}{kT} \right) j \rho e Z^*$$



Physical Mechanism - Atomistic View

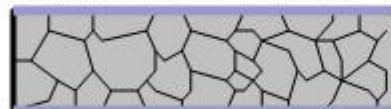


Physical Mechanism – Microstructure View

Bamboo microstructure - single grain across line width for vast majority of line



Multiple-grained microstructure has at least two grains across line width for vast majority of line



Near bamboo microstructure is a mix of bamboo and multiple-grained, but mostly bamboo



Physical Mechanism

Black's Equation

$$t_{50} = A j^{-n} \exp\left(\frac{\Delta H}{kT}\right)$$

A is a materials constant

n is the current density exponent

n=1 if the lifetime is limited by void growth

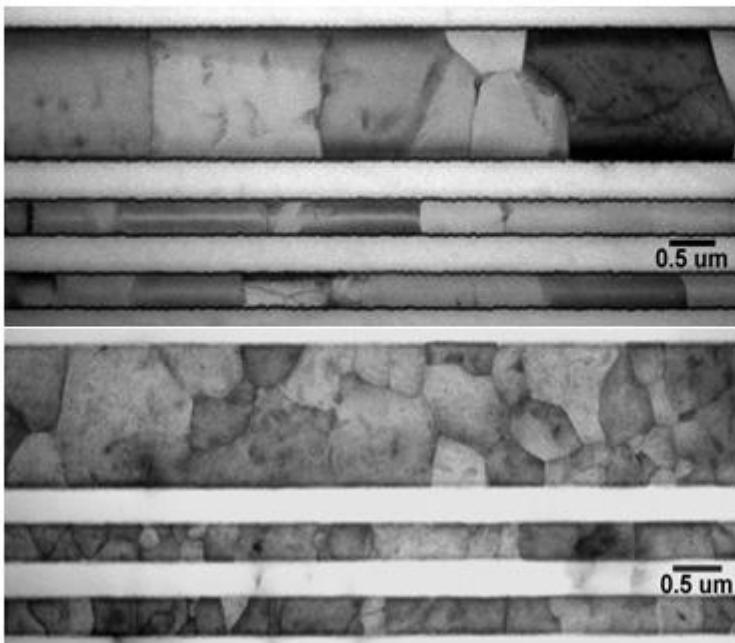
n=2 if the lifetime is limited by void nucleation

ΔH is the activation energy

Depends on which diffusion path is dominant

(i.e., grain boundary diffusion, interface diffusion, bulk diffusion)

Typical AlCu Microstructures

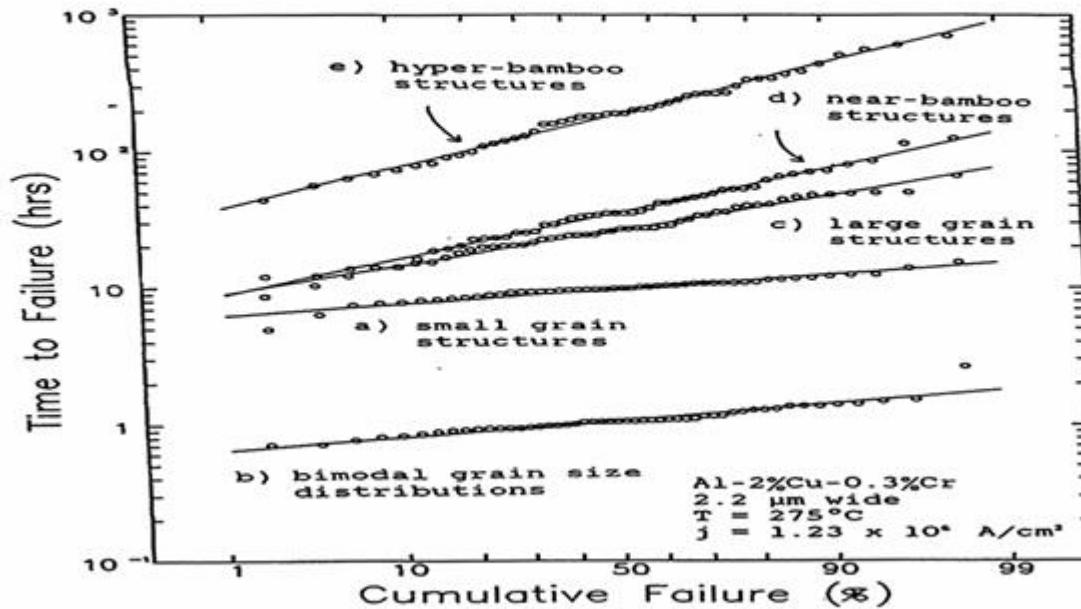


Plan view
TEM
micrographs

- (a) Dual Damascene line, near bamboo
- (b) Dual Damascene lines, bamboo
- (c) RIE line, multiple-grained
- (d) RIE lines, near bamboo

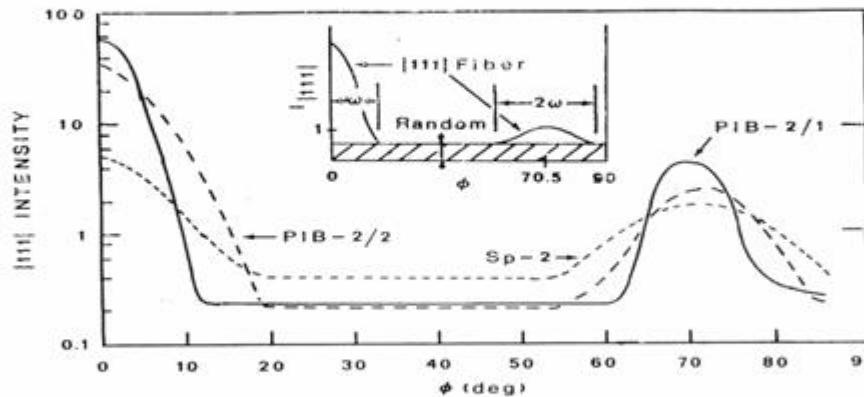
Grain Size & EM

J. Cho and C.V. Thompson, APL 54 25 (1989)

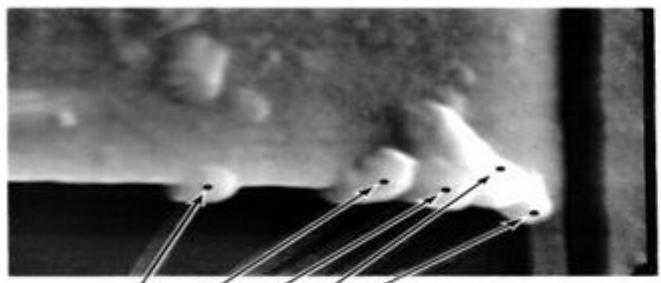


Al Crystallographic Texture and EM

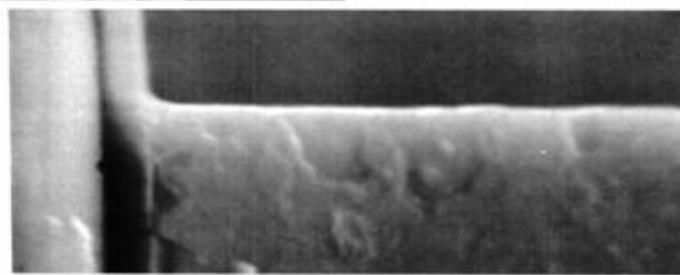
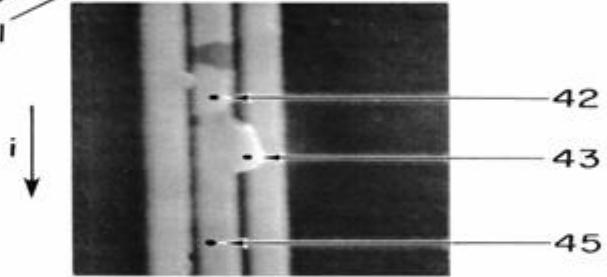
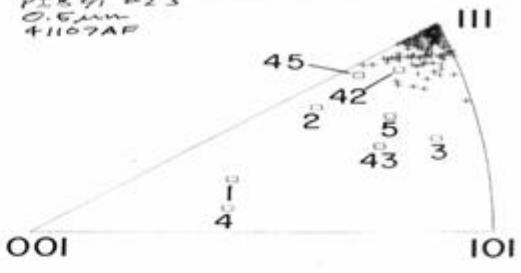
D.B. Knorr, et al, APL 59 3241 (1991)



APL, 59, 3241 (1991).



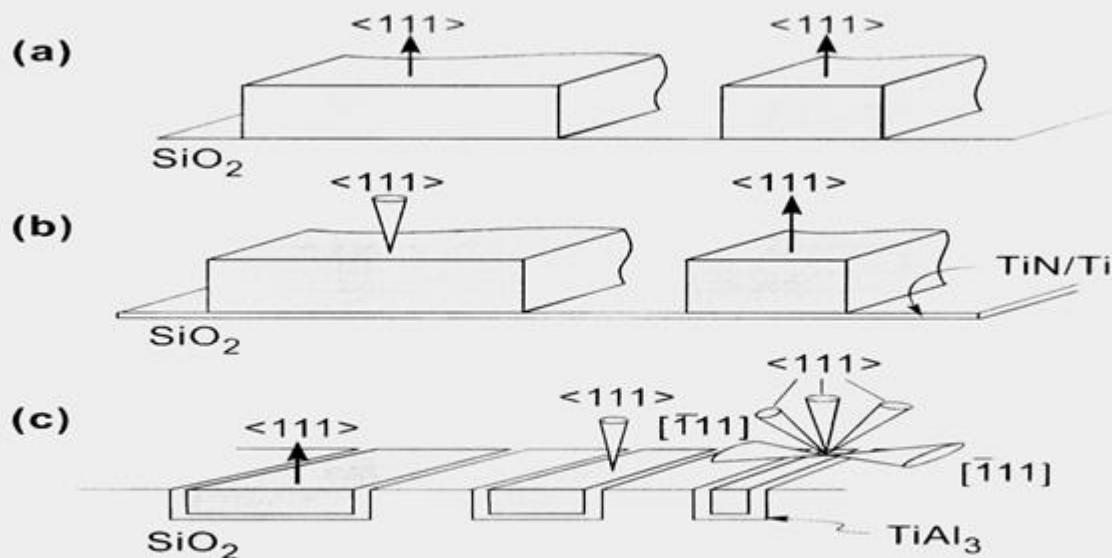
PIC 5/1 #23
0.6µm
1107AF



Rodbell, et al.

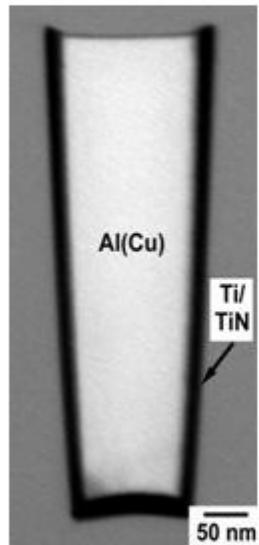
Texture in Narrow Al Lines

J.L. Hurd, et al., APL 72 326 (1998)

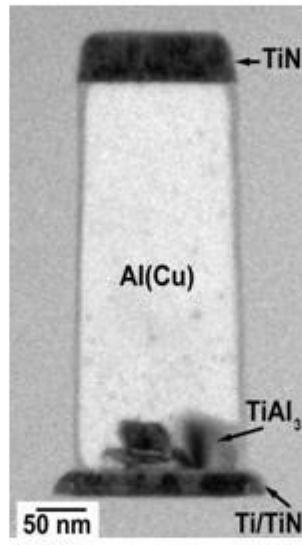


Schematic diagram depicting $<111>$ plane normals to those (111) planes influenced by various interfaces for (a) a planar film etched into lines, (b) a planar film with a TiN/Ti under-layer and (c) three damascene line widths, containing appreciable TiAl_3 , which results in a tri-modal (111) orientation distribution as the lines narrow.

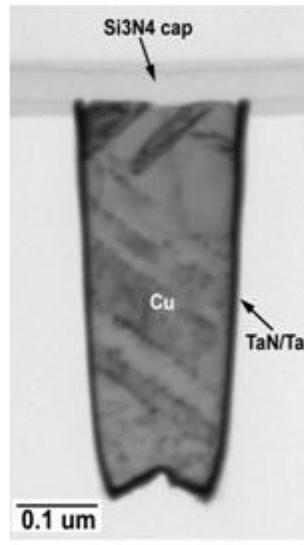
TEM cross sections of multilayered thin film interconnection lines



AlCu - Dual
Damascene



AlCu - RIE

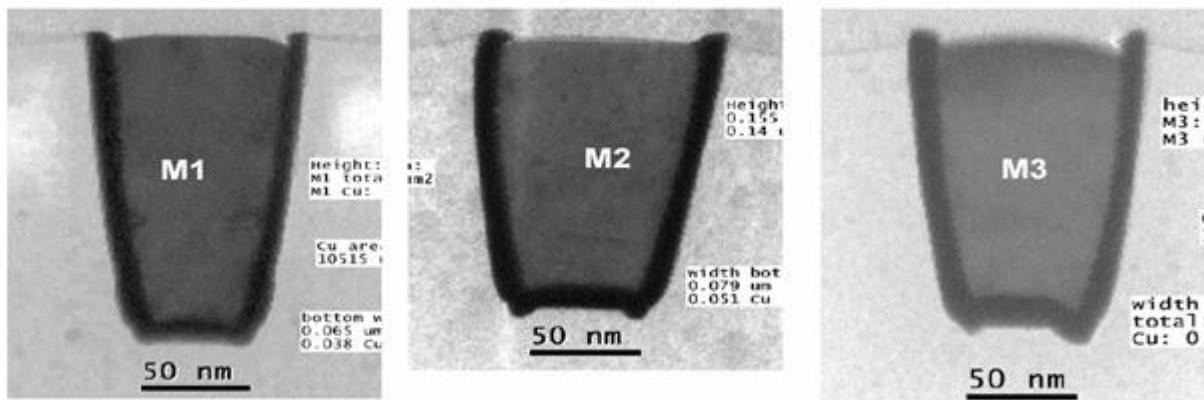


Cu - Dual
Damascene

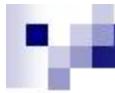
Integrated Circuits; Cu Wiring Microstructures (nm) –

courtesy of L. Gignac IBM Research (2004)

Comparison of M1, M2 & M3 line profiles at similar magnifications



M1 is deep and narrow compared to M2 and M3 but all areas are similar



Outline

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 - EBSP
 - HyperNeX – Metrology Tool Development
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- Conclusions

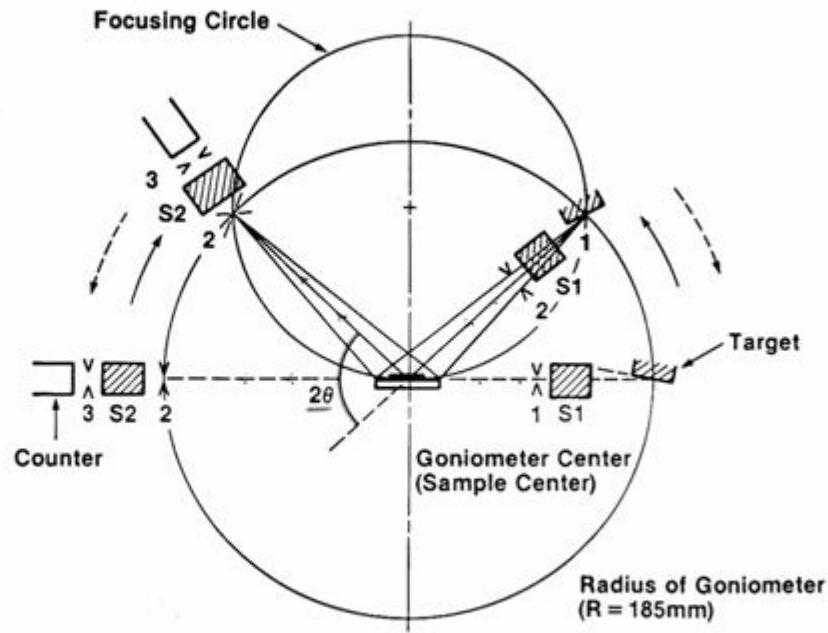
Geometry of Rigaku Theta-Theta Wide Angle Goniometer

Bragg - BRENTANO

$\theta/2\theta$ coupled

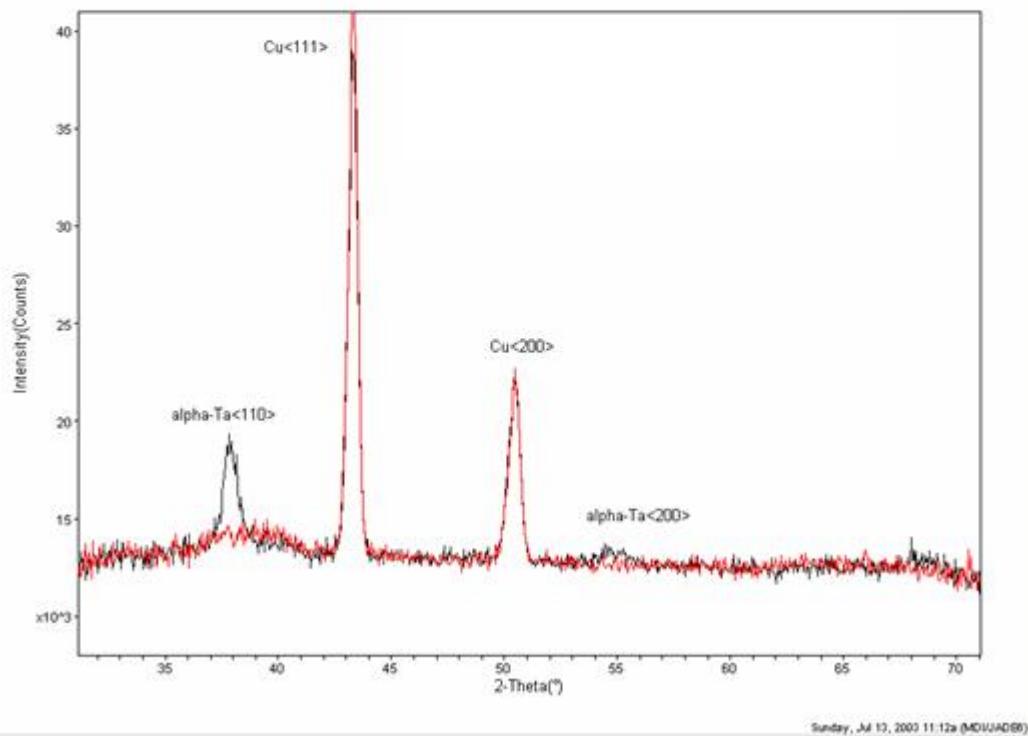
ROCKING CURVE

2θ fixed
Sample fixed

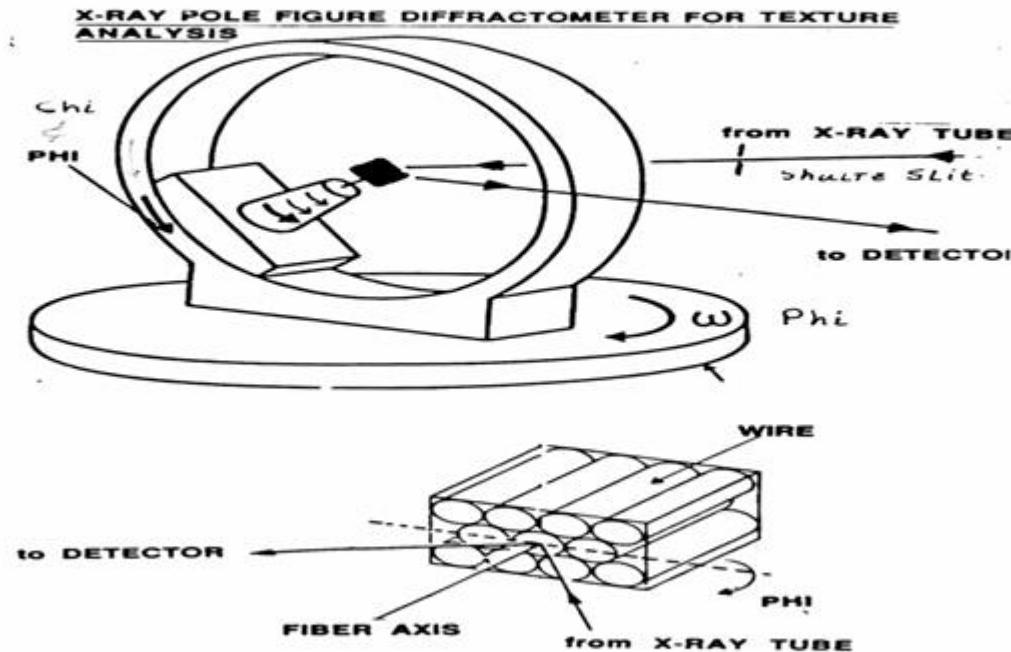


S1, S2: Soller Slit
1, 2, 3: Slit Inserting Port
(1-DS, 2-RS, 3SS)

Theta – 2Theta



Four - Circle Diffractometer



XRD vs. EBSP (Inverse PF)

J.L. Hurd, et al. Mat. Res. Soc. Symp. Proc. 343 653 (1994)

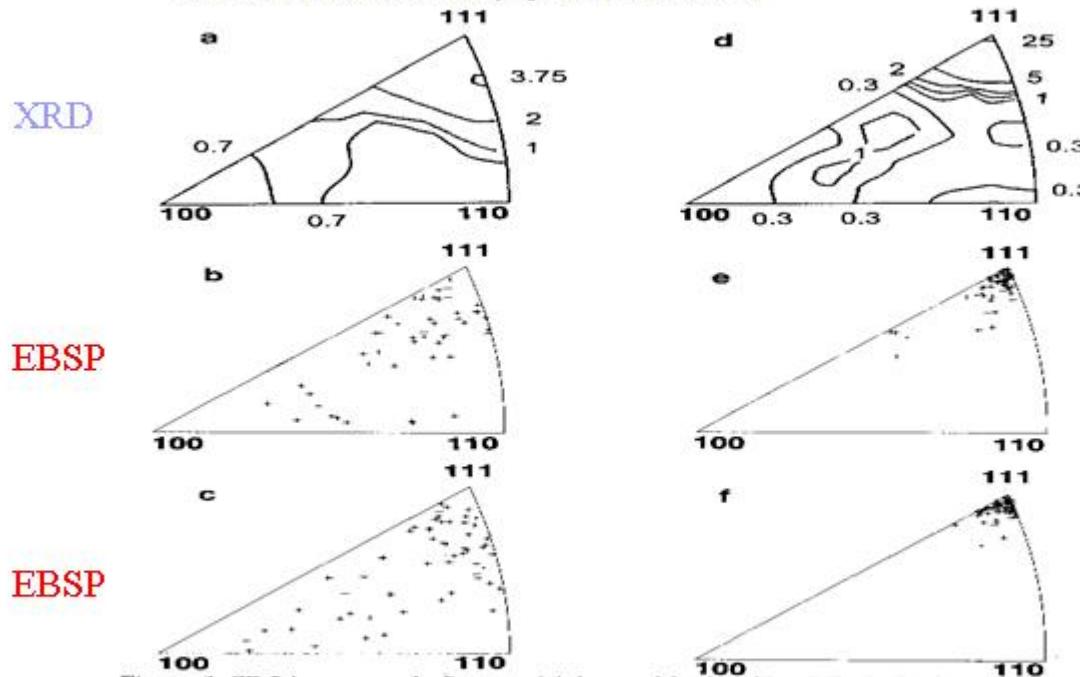


Figure 1. SP-2 inverse pole figures: (a) from a blanket film (XRD), (b) for 50 grains from a $100 \times 100 \mu\text{m}^2$ pad region on a chip (BKD) and (c) for 60 grains from a $0.6 \mu\text{m}$ wide line (BKD). PIB2/1 inverse pole figures: (d) from a blanket film (XRD), (e) for 56 grains from a $100 \times 100 \mu\text{m}^2$ pad region on a chip (BKD) and (f) for 60 grains from a $0.5 \mu\text{m}$ wide line (BKD).

Area Detector; Multiple Debye Rings



Al (111) + Si spots

$2\theta = 40^\circ$

$\theta = 28.5^\circ$

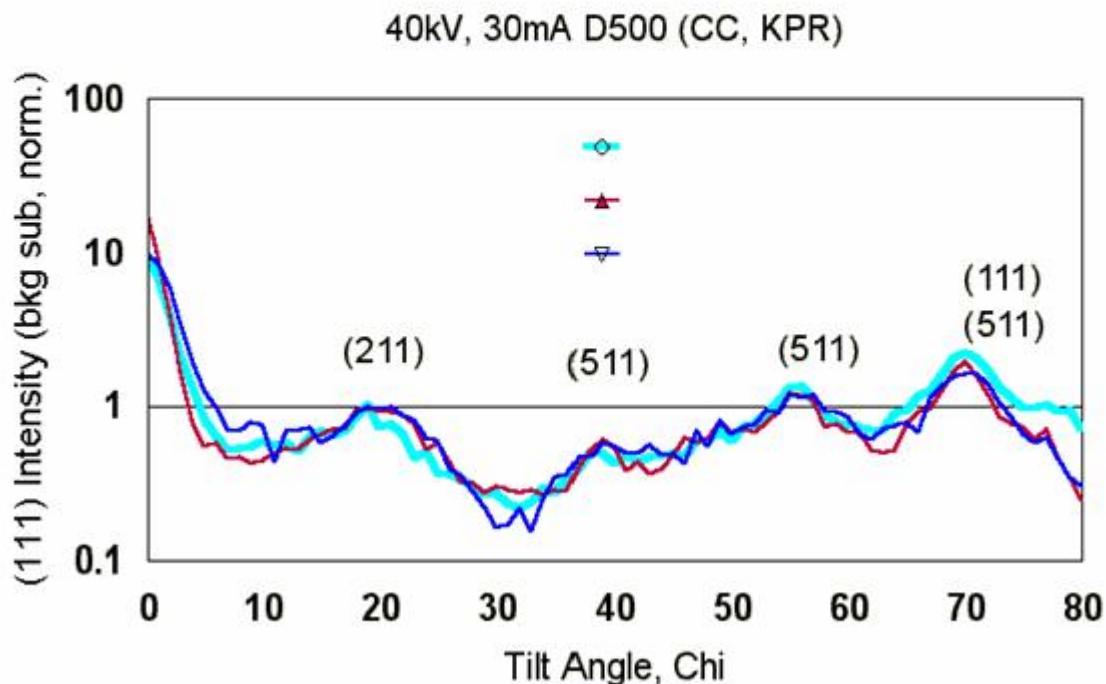
40 kV, 100 mA Cu radiation

10 s / frame



Cu (111), (200),
(220), (311)

Plated Cu (111) Fiber Texture



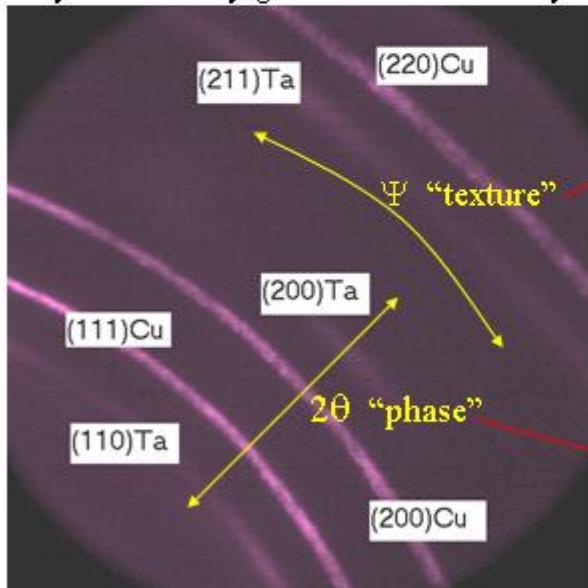


In-line Metrology (e.g.,)

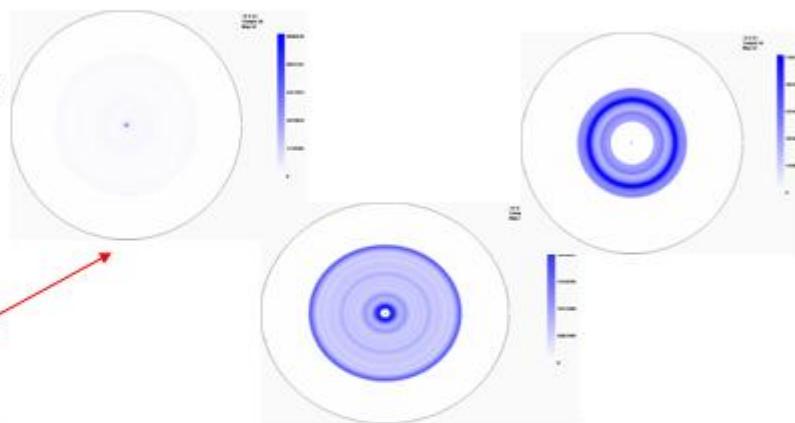
- Process control
 - Process stability**
 - Process excursions?**
- Process development and qualification:
 - Barrier and seed layers** - selection of materials and deposition conditions
 - Electroplating** – optimization of bath chemistry and plating conditions
 - Annealing** - optimization of temperature, ramp, time.
- Tool qualification:
 - Performance** of new (maintained) production tools (chambers)
- Development:
 - Device and reliability improvements through microstructure control
 - Fundamental studies - microstructure development and evolution during processing

Simultaneous Phase/Texture/Thickness Information Using An Area Detector

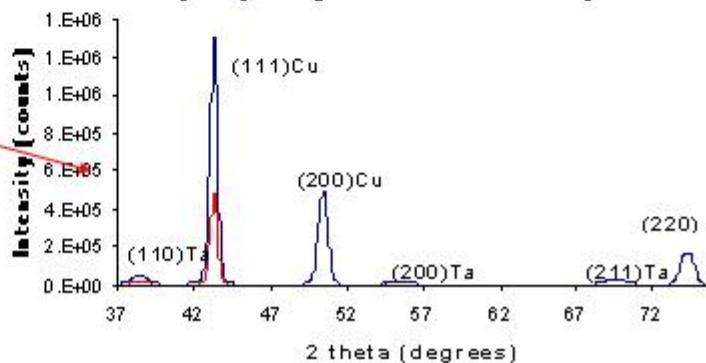
An area detector combined with a novel analysis method enables rapid quantitative analysis on many grains simultaneously



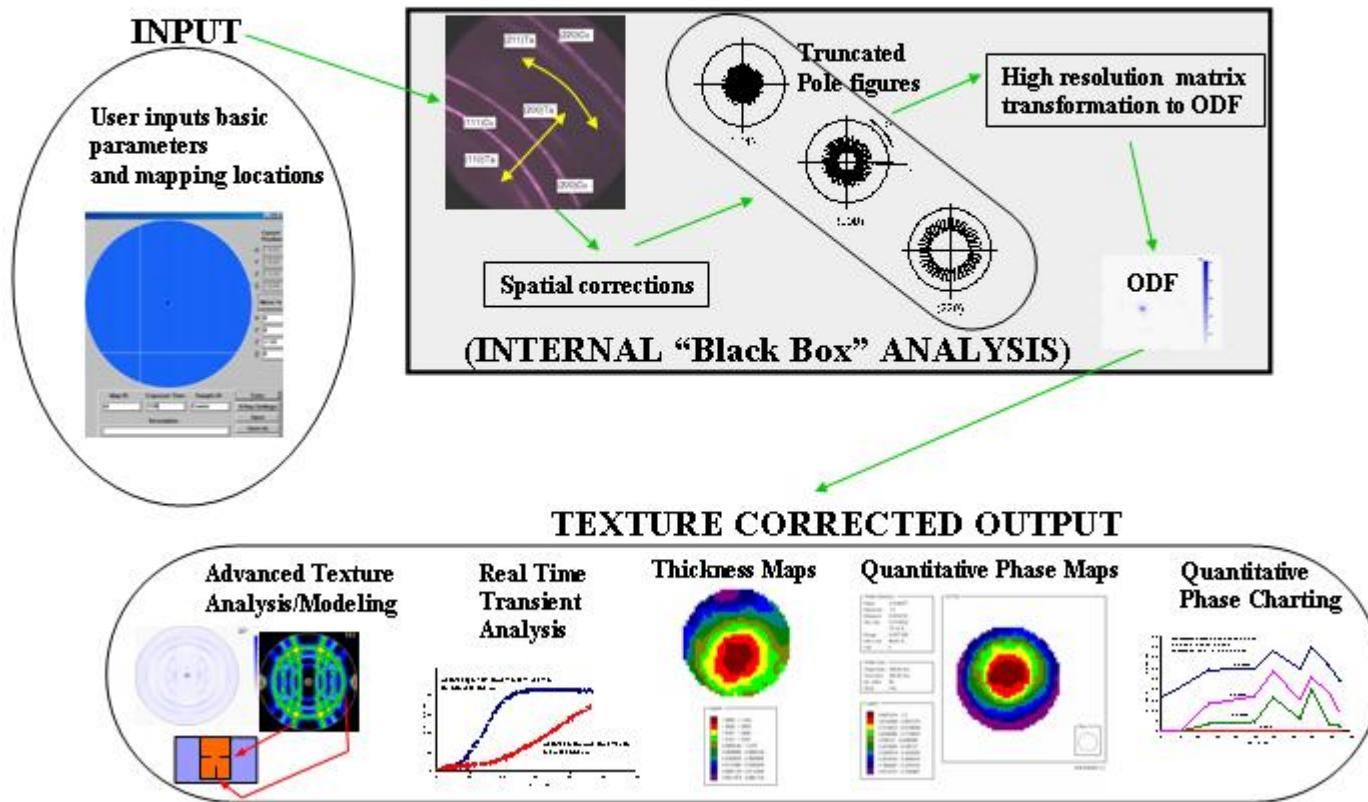
0.5 micron electroplated copper deposited on 300A thick Ta barrier layer



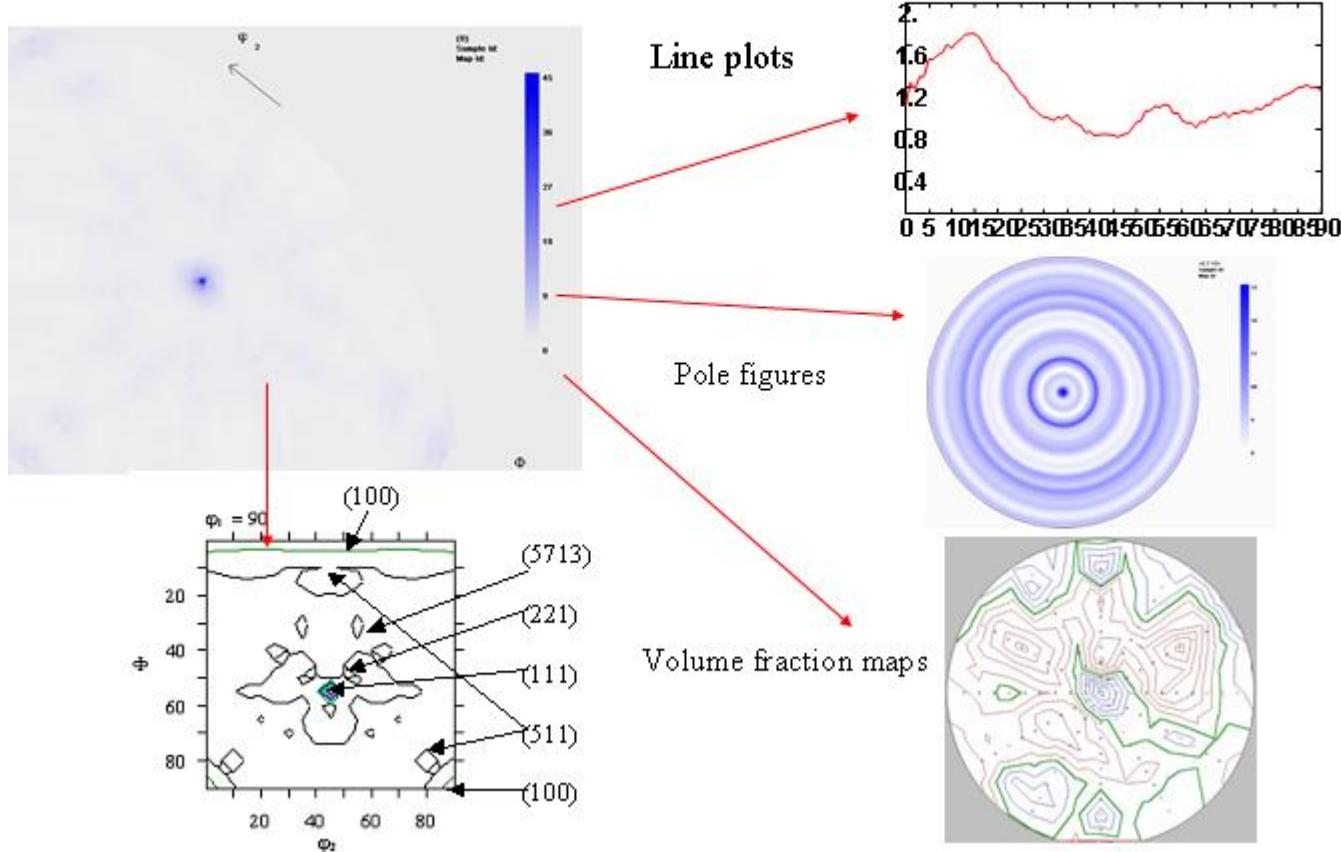
3 incomplete pole figures for both Cu and alpha-Ta



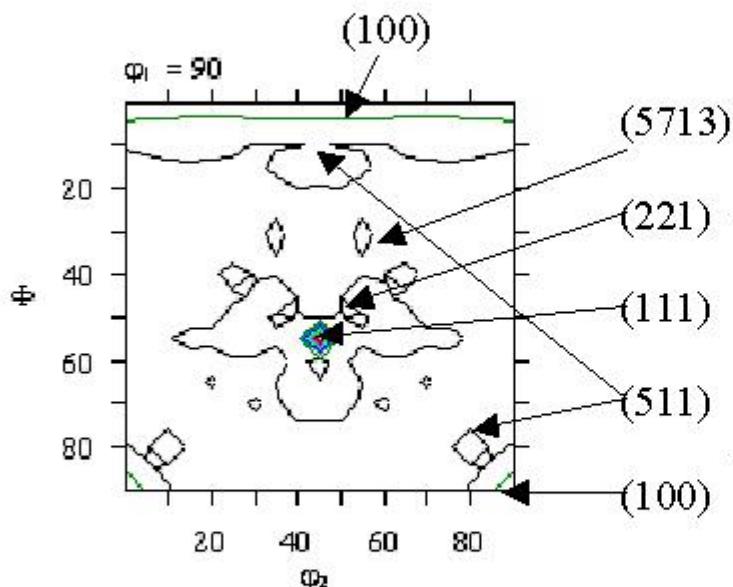
Fab Oriented Input-Output Protocols



Quantitative Texture Analysis (ODF) -



Quantitative – Texture Volume Fractions



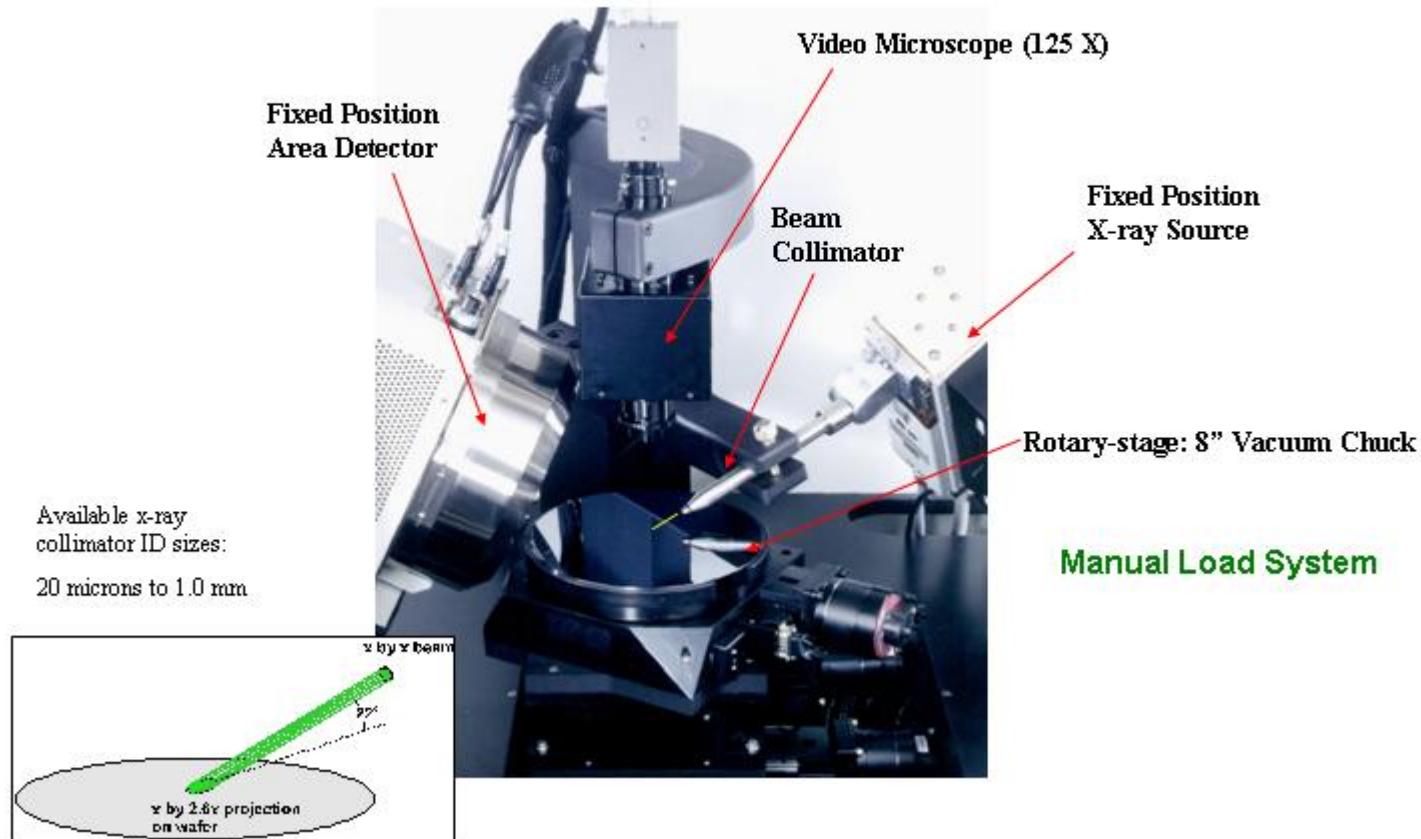
$$\frac{dV}{V} = f(g)dg$$

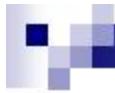
Where: dV is the volume of crystallites that have the orientation g within the element of orientation dg , and V is the total sample volume.

$$dg = \frac{1}{8\pi^2} \sin \Phi d\varphi_1 d\Phi d\varphi_2$$

Volume fractions of texture components with cyclic fiber textures are determined with accuracy better than 5% and precision of 0.5%

HyperNex (200 mm) Prototype (IBM 2001 – 2003)





HyperNex (200 mm) Prototype (IBM 2001 – 2003)



Space/time maps and trend charts of:

- Phase composition
- Crystallographic texture
- Relative grain size
- Thickness

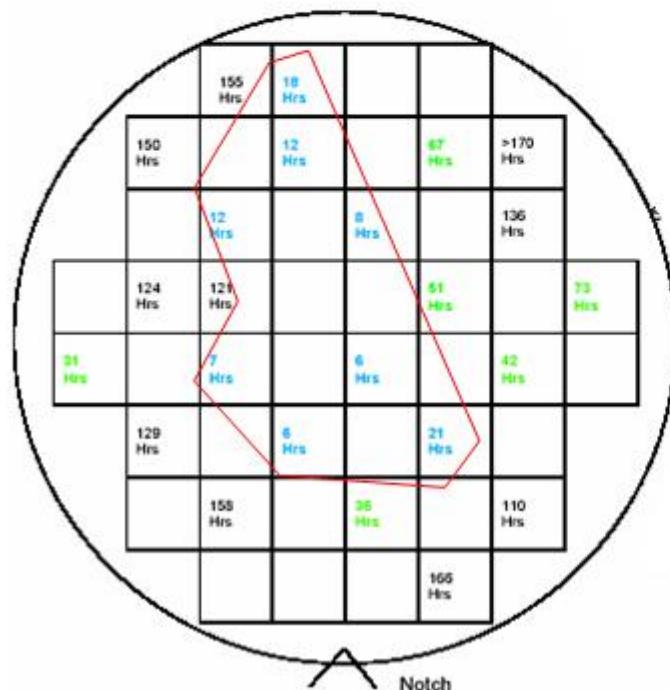
Liner quality control

Process stability

The prototype 200 mm inspection tool at the IBM ASTC in EF, NY. (part of JDA).

Electromigration & EP Cu (111) Texture

200 mm Plated Cu / Ta Lines
Electromigration (EM) - Time to First Fail (hours)

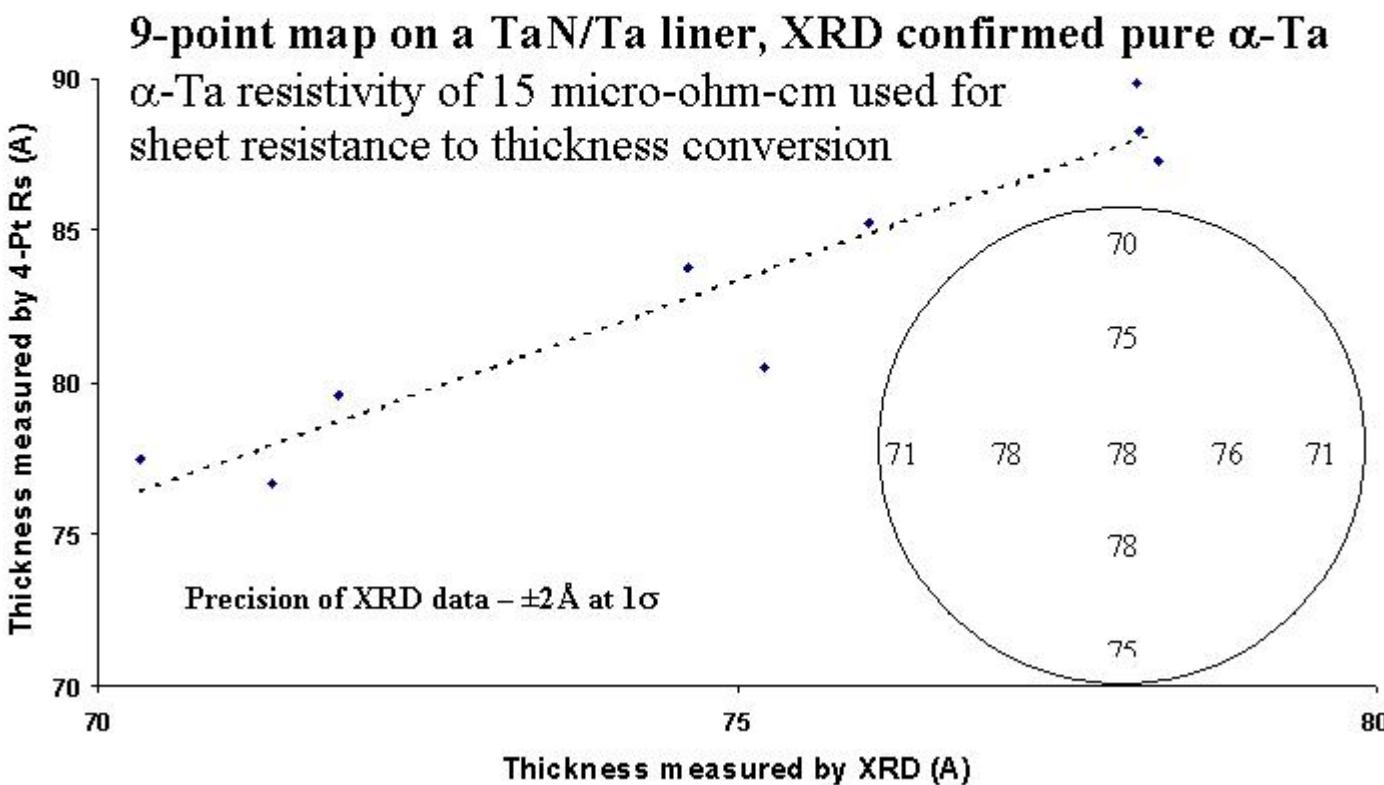


Time to first failure Cu (111) Texture Strength

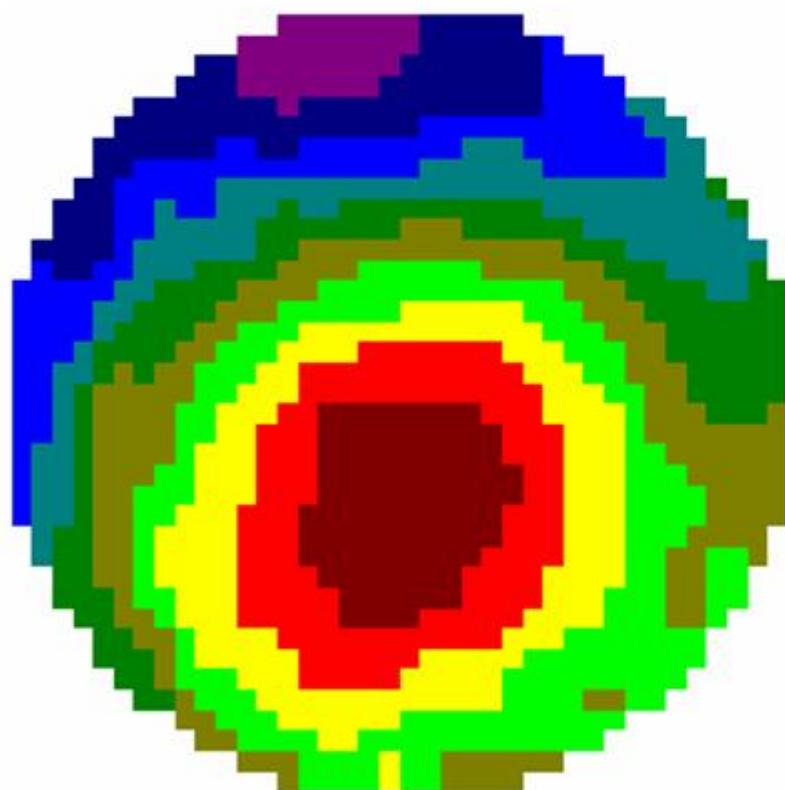
< 25 hours	low*
25-75 hours	medium*
> 75 hours	high*

HyperNex - 200 mm beta tool (ASTC)

4-Point Probe Sheet Resistance and XRD Thickness Measurements

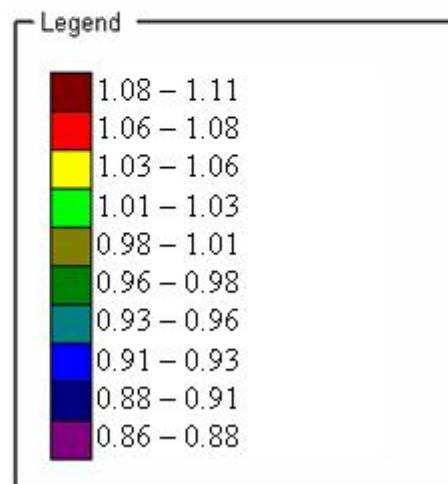


Thickness Maps for Process Control



294 point alpha-Ta thickness map

Thickness normalized to nominal liner thickness.

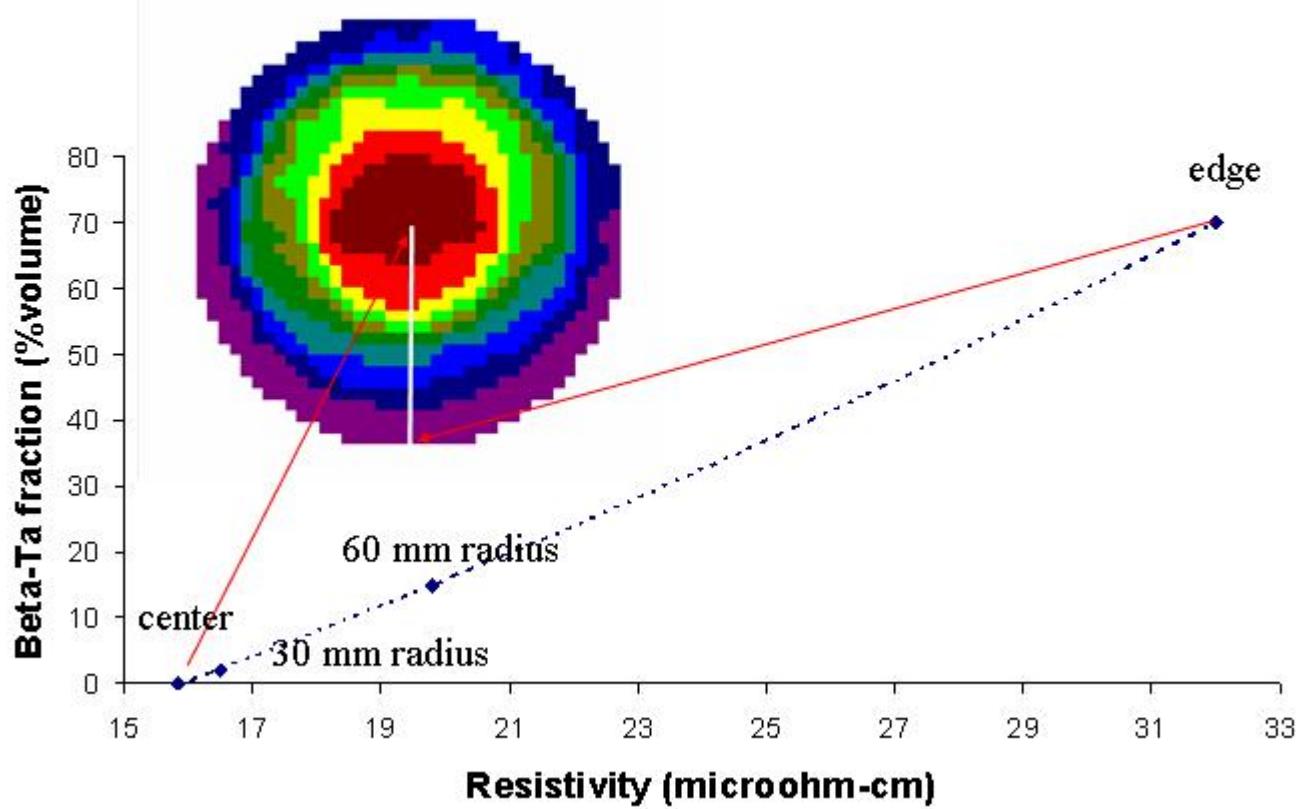




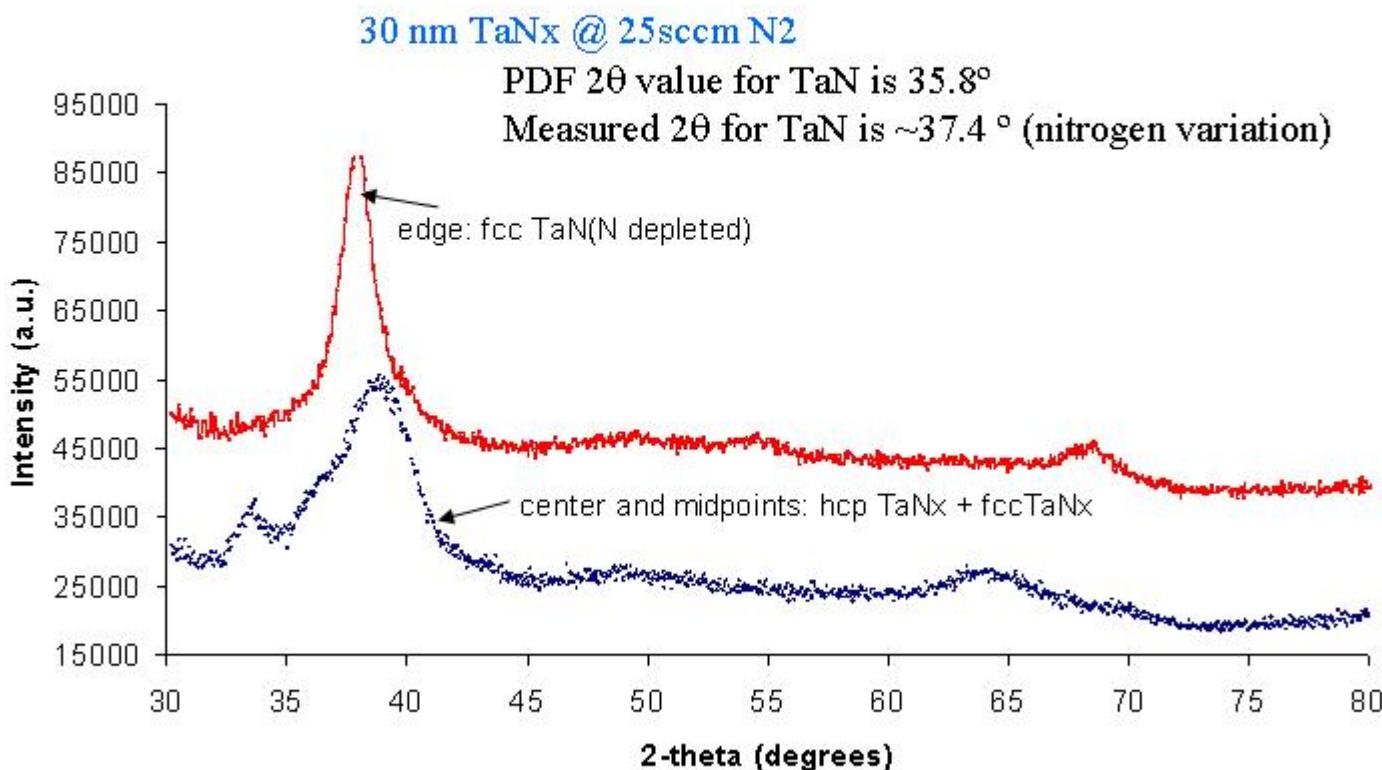
Control of TaN_x

- Crystalline TaN is needed to stabilize α -Ta (bcc-Ta) barrier layer (Edelstein, 2001 IEEE)
 - α -Ta? → lower resistivity and better adhesion than β -Ta
 - 100-400 Å HCP TaN (IBM's original protocol) with (110) or (001) fiber texture and/or FCC TaN with (111) and/or (110) fiber texture. Amorphous TaN<100 Å not sufficient
- TaN_x phase and texture are controlled by a narrow window of PVD conditions such as N₂ flow, temperature and time (film thickness)
- A narrow process window → potential for TaN_x phase and texture to vary across the wafer and from lot to lot (for example kit replacement during maintenance may move the established process window)

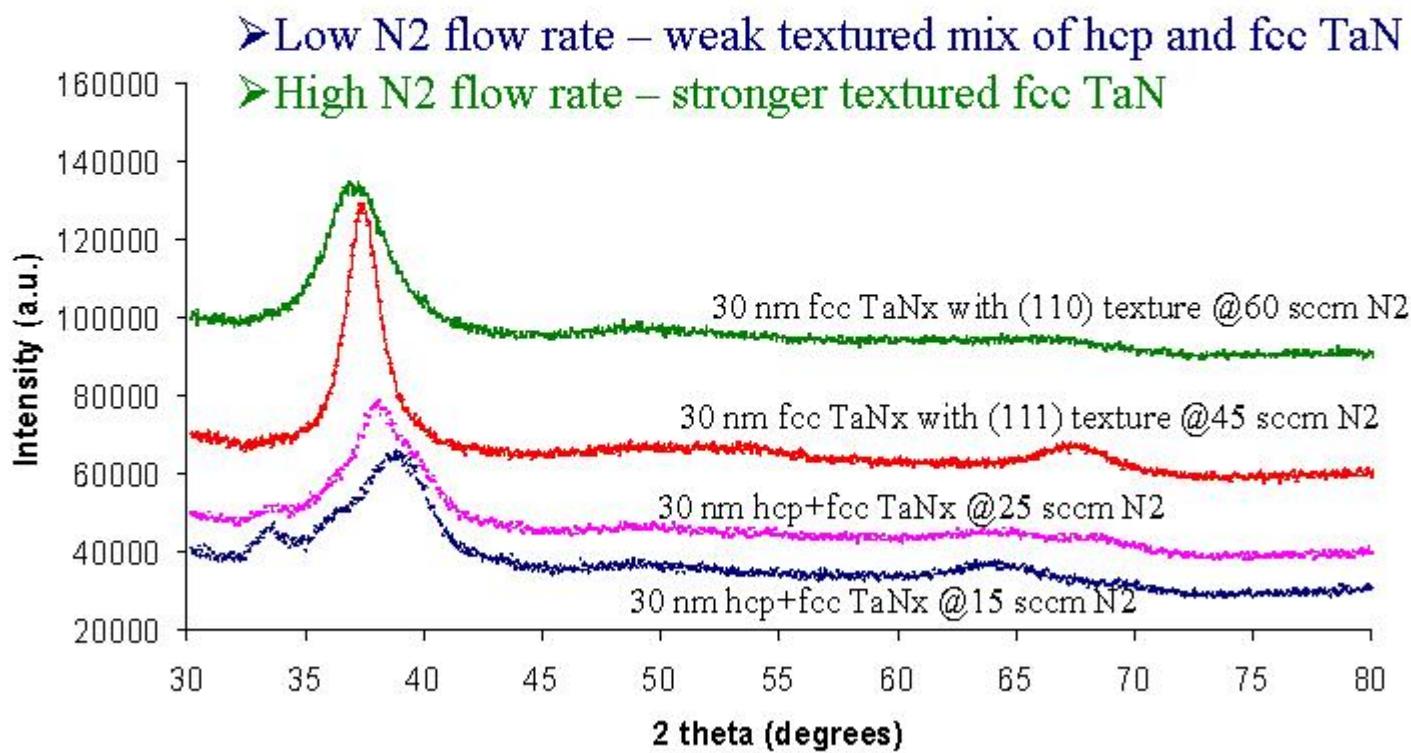
Phase Maps & Sheet Resistance Measurements



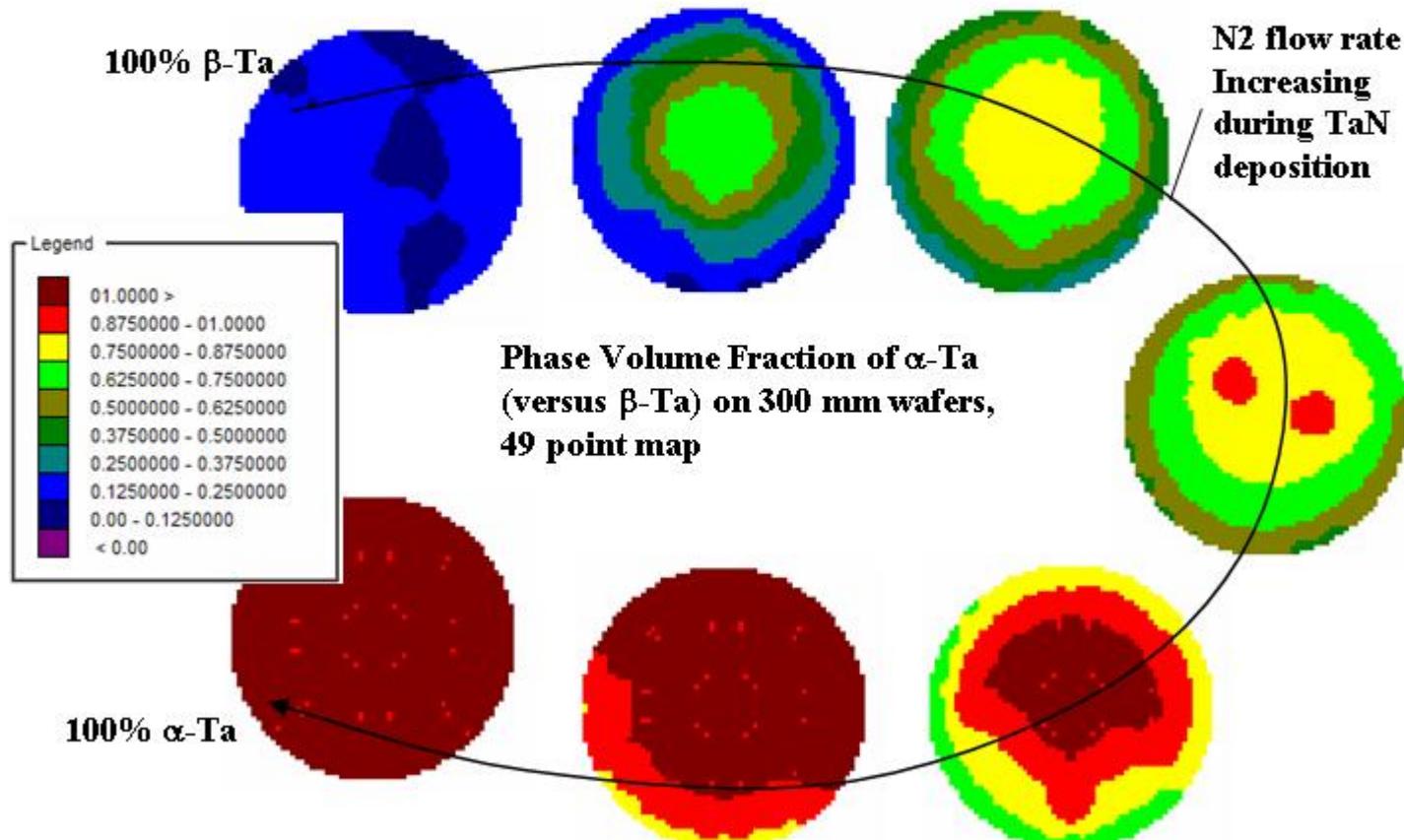
TaN_x Phase Varies Across Wafer



Phase and Texture of TaN_x Films are Controlled by Deposition Parameters

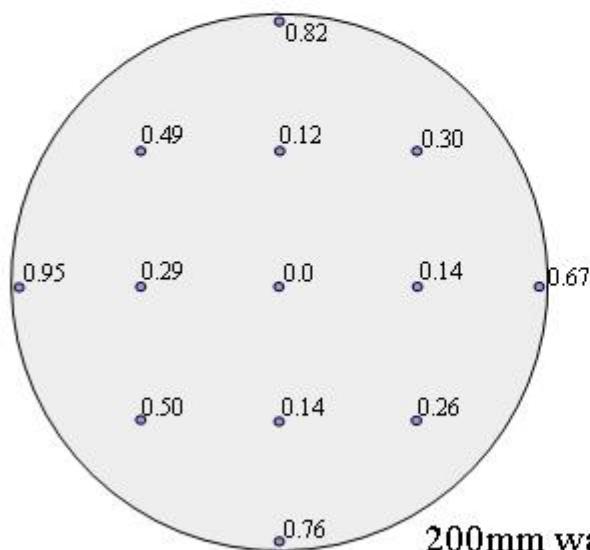


EFFECT OF TaN LINER ON Ta PHASE

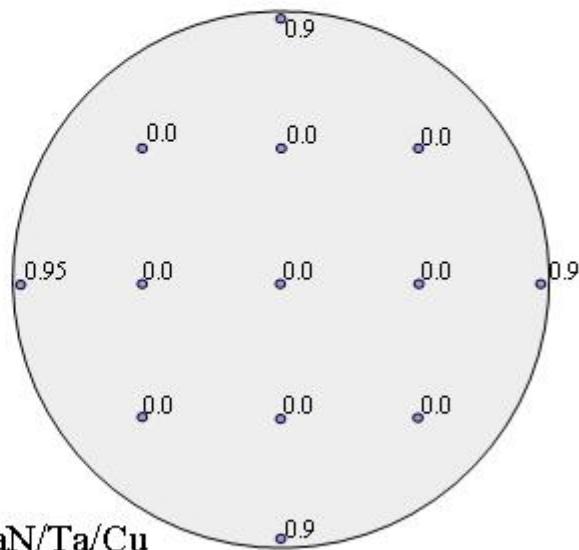


Wafer Map of β -Ta Before and After CMP (Trench versus Overburden)

β -Ta measured before and after CMP suggests no β phase at center, virtually all β phase present in overburden at mid-radius and significant β phase present in trench near edge



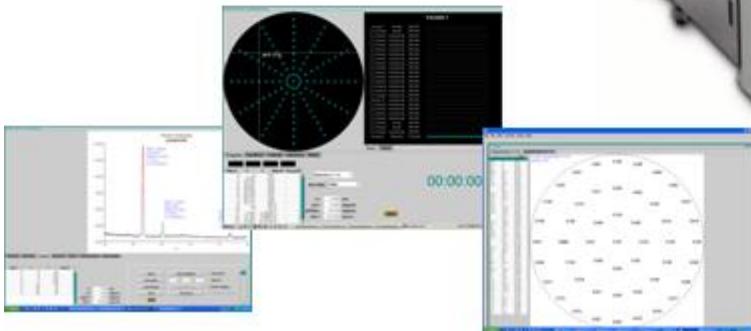
200mm wafer, TaN/Ta/Cu
0.2 μ m line test structures



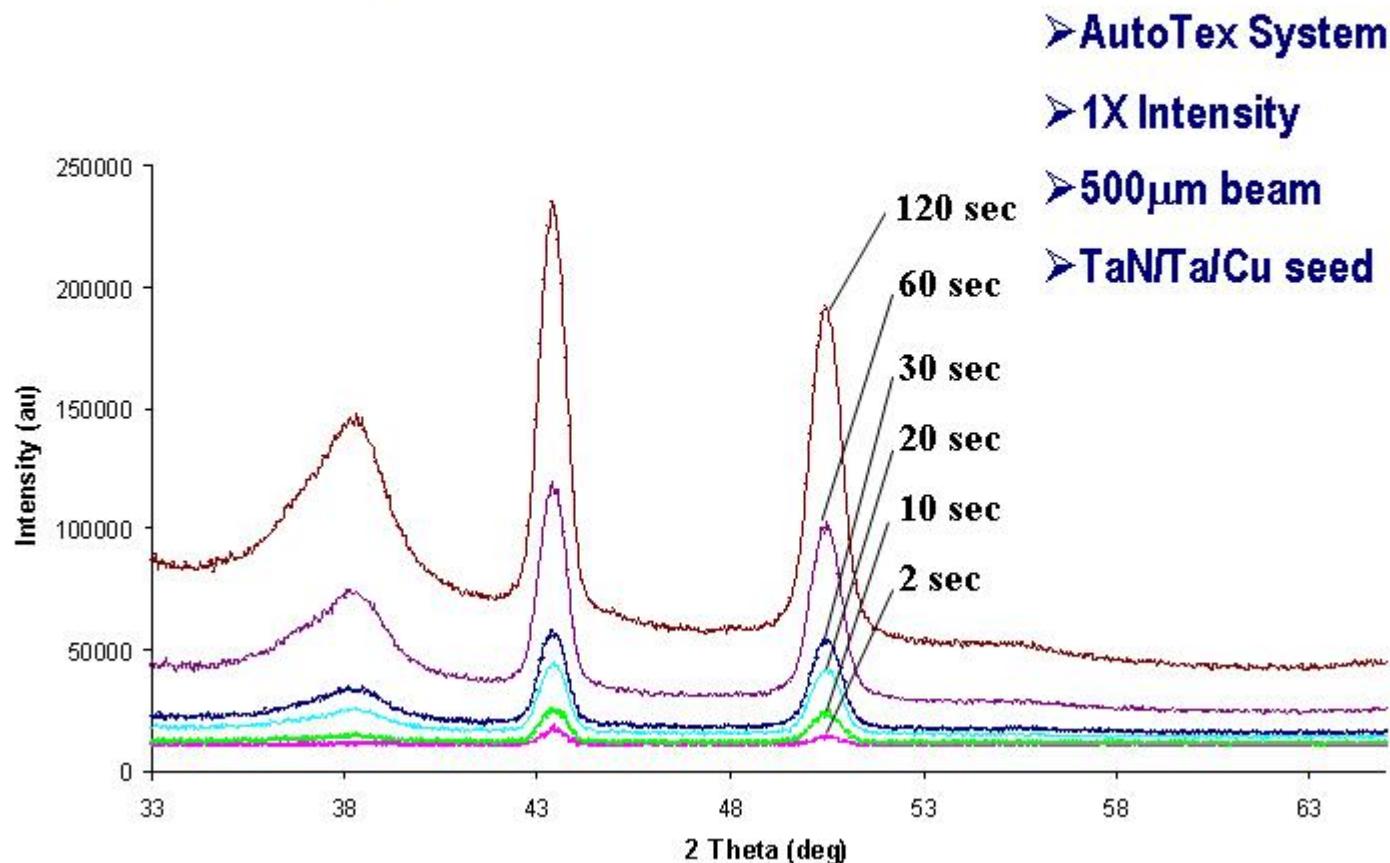


CuTex – 300 mm Fab System

- System #1 Delivered to
IBM 2-18-03
 - 3rd party S2-S8 review
 - SECS-GEM Compliant
- System #2 - 9/03 (TI)
royalty to IBM)

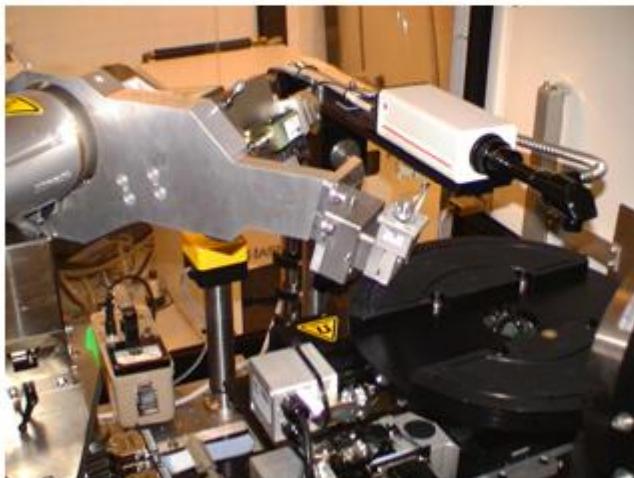


Intensity Versus Data Collection Time



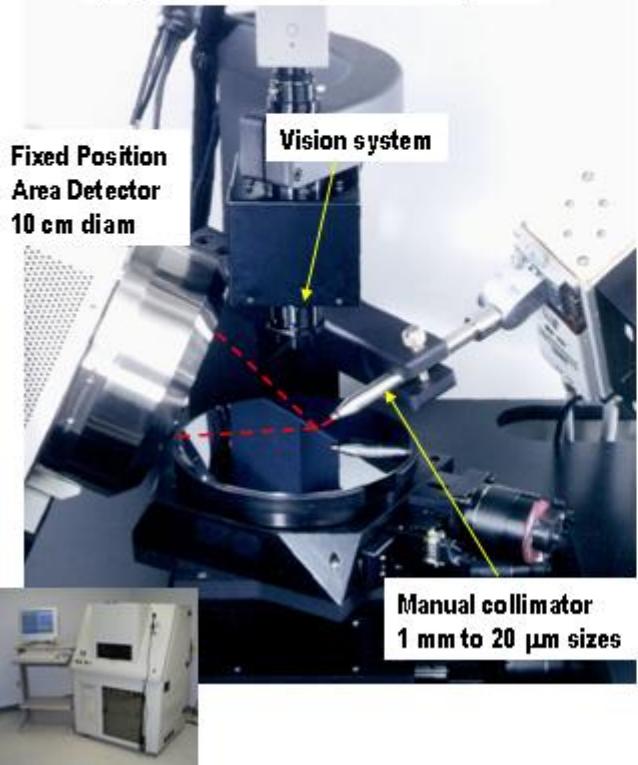


CuTEX SYSTEM

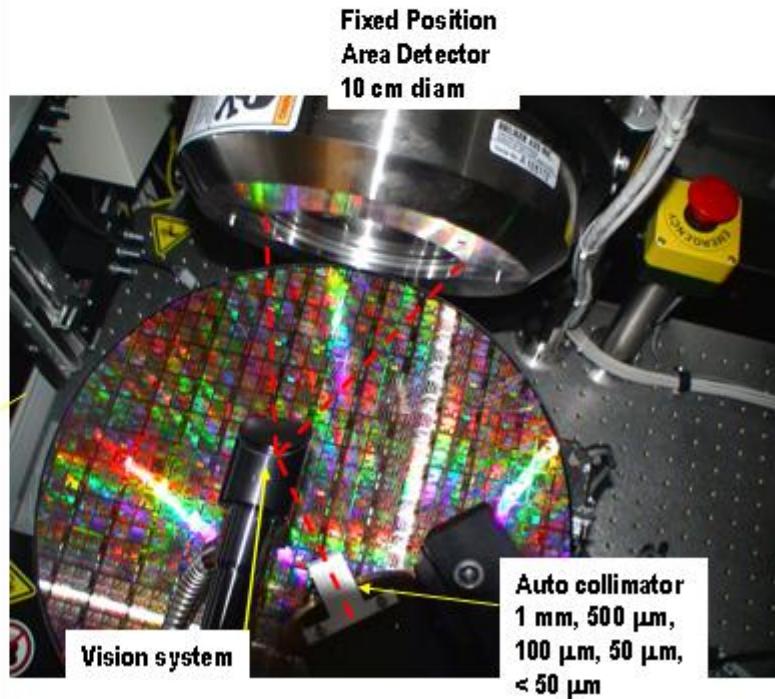


Measurement Layout

200 mm Manual "Beta" System
(2 yrs at Fishkill Pilot Line)



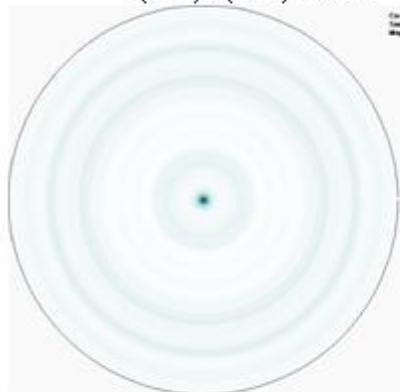
300 mm Automated System



Range of Cu Texture Variation

(111) Pole Figures

(111)+(511) fibers



Wide lines >1 micron

(111) + (511) fibers
Bottom + sidewall



Intermediate width lines
0.4 – 1.0 micron

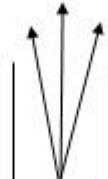
(111)[110]+(111) fiber



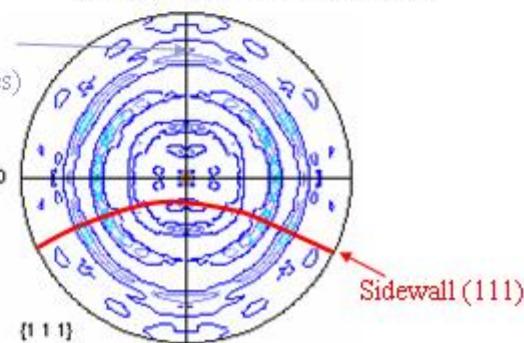
Narrow lines < 0.4 micron

Texture:

- dependent on line geometry
- dependent on location on the wafer (more random and “tilted” at the edge)

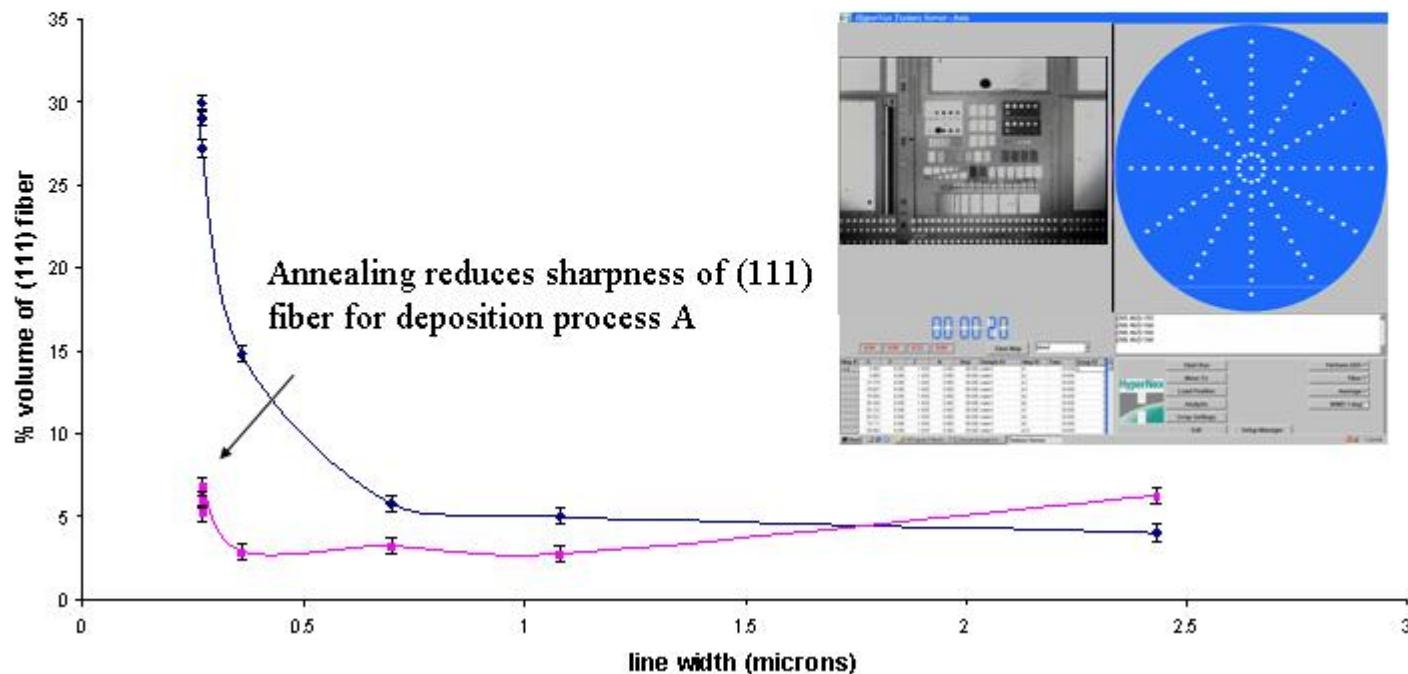


Bottom (111) tilted 5 degrees)

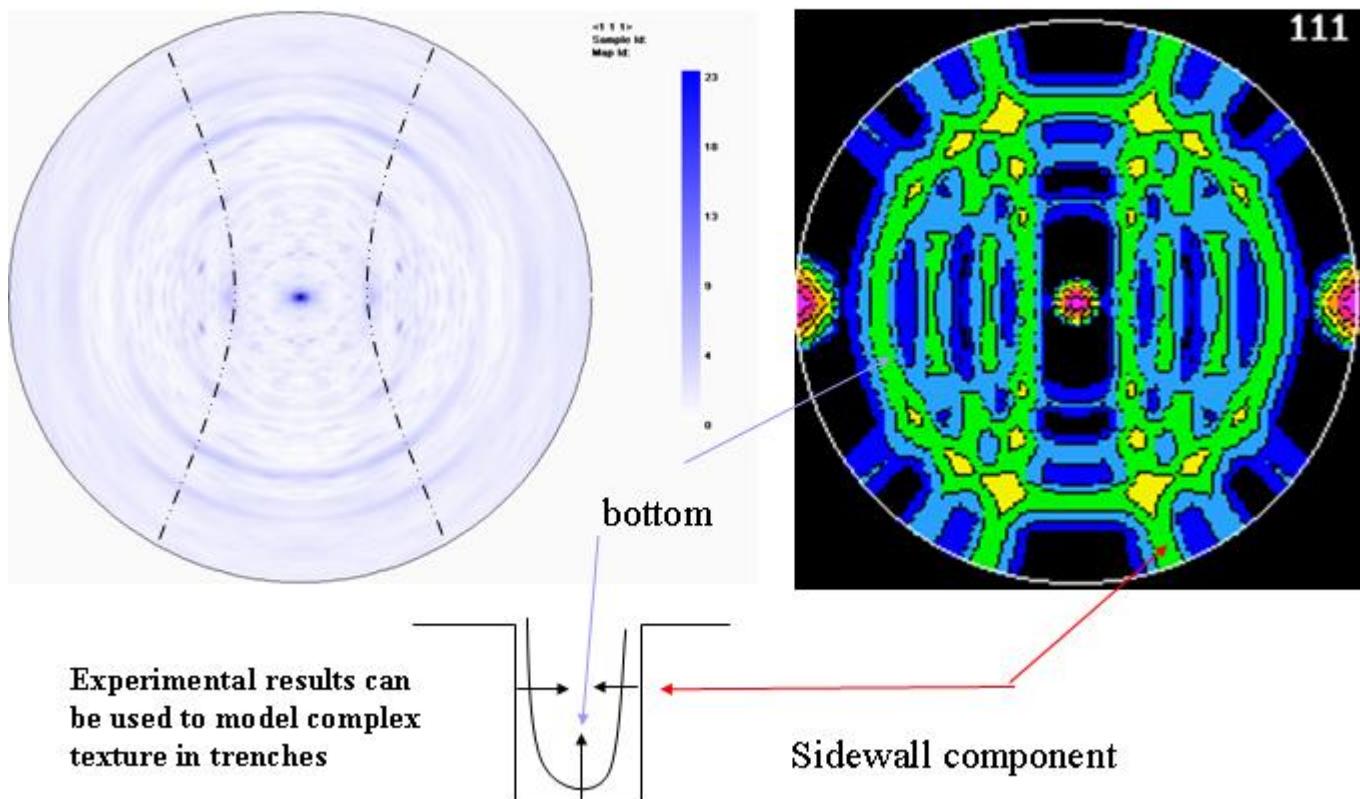


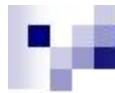
Measurements On Patterned Cu Structures

Texture evolution in electroplated Cu lines at room temperature versus annealing at 300C



Crystallographic Texture in Lines





SUMMARY

- R_s measurements will not work at << 10 nm film thickness
- X-ray diffraction metrology tool - **metal thickness, crystallographic phase and texture** in a time frame suitable for 300 mm online applications developed
- Speed, precision and mapping capabilities
 - process qualification
 - process development
 - process stability (metrology)



Acknowledgements

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IBM Microelectronics Division, East Fishkill, NY 12533

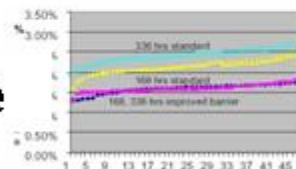
Cu Microstructure

- Jay Chen, *Applied Materials*, International Interconnect Conference, April 2002, “Improved copper microstructure leads to:”

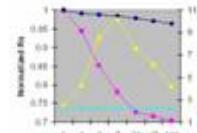
- lower defect count



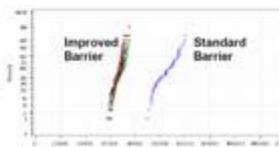
- Improved stress-migration resistance



- lower electrical resistance



- improved electromigration resistance



- improved adhesion

